Acoustic Emission during Initiation of a Shear Bandin a Metallic Glass as a Method for Verification of the Existence of Scale Invariance

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Abstract—Using the acoustic emission method, we have determined the probability density distribution function of shear band lengths in a metallic glass and demonstrated its independence of stoichiometric composition of glass and experimental conditions. The power-law form of this distribution confirms independently the observed quadratic scaling in the time dependence of the rate of shear processes in metallic glass.

1. INTRODUCTION

Scale invariance (or scaling) indicating the general nature of physical phenomena at different scale levels is undoubtedly important in various fields of natural science [1–4]. In the case of scaling invariance, a phenomenon under investigation exhibits self-similarity; i.e., changing in space and time, the phenomenon reproduces itself in varying spatial or temporal scales. From the analytical point of view, this implies the existence of a power-law relation between main characteristics of the given phenomenon [4]. Self-reproduction of physical phenomena with scale invariance makes it possible to simulate and study these effects in laboratory conditions on small scales and to extend the results to similar large-scale effects. In particular, it was substantiated in monograph [5] based on the continuum mechanics that the shear band front appearing during the fracture of the earth crust is a macroscopic seismodislocation with the corresponding long-range field of stresses. Analogous conclusions were formulated in [6] for the shear band front in a metallic glass. Despite different scales of the phenomena considered in these publications, it is natural to put forth the hypothesis on their scale invariance and analyzing the kinematics of shear bands in metallic glasses, to extendthe results to the description of shear processes in the earth crust.

Self-organized criticality in the behavior of metallic glasses, which is analogous to that in granular media and tectonic processes, was noted by some authors on the basis of investigation of stress removal accompanying the propagation of shear bands [7–9].

However, this process consists of two stages, viz., rapid formation of the band front followed by a relatively slow shear of one part of the sample relative to the other over the band [10, 11].

In particular, it was found in in situ experiments [12–14] on the kinetics of initiation and subsequent evolutionary growth of a shear band in a metallic glass that the time dependences of the shear band front velocity is of an asymmetric pulsed type and includes conditionally two stages: (i) rapid (over time $\tau_i < 30$ μs) increase in the front velocity from zero to a certain maximal value $V_{\max}$ (smaller than 5 m/s) and (ii) slow (about 300 μs) decrease. It was found that the rates of shear processes in a metallic glass at the stage of conditional deceleration from the maximal velocity to its final value are characterized by the power-law distribution of average velocity (or instantaneous velocity within the time measuring error) in form

$\langle V(\xi)\rangle \sim 1/\xi^{\alpha}$ (ξ - is the time at the instant of measurement), where $\alpha \sim 2$; this was confirmed by numerous experimental data [13, 14].

The power-law dependence of the shear band velocity (and, accordingly, shear band length if we disregard a constant term), which has been revealed in [13], indicates scale invariance of the process of shear band propagation at the conditional deceleration stage. The consequences and prolongation of interpre- tations of the detected invariance were also considered in detail in [14]. In addition, an analytic description was proposed for the observed scaling, which in spite of its approximate nature, can serve as a universal application to any shear process in continuum mechanics because only the power in the function of the probability density power-law distribution over the shear band lengths serves as a control parameter. This circumstance can be used, in particular, for estimating the velocity and time of shear processes in the earth crust, which is very important for estimating the dynamics of possible earthquakes.

In the derivation in [14] of the form of the function of distribution over the shear band lengths at the stage of propagation from the maximal velocity to its final value, we used the proportionality of the shear band length to the local stress removal [15, 16]; in this sense, the function of distribution over shear band lengths must repeat the distribution function over stress removals to within a constant normalization factor. Such an approach is justified, but is indirect. Since the time evolution of the shear band length is continuous, the shear band length distribution function must pre- serve its form at the first stage (acceleration) as well as at the second stage (deceleration down to the final value of the shear band velocity). However, an analogous distribution over shear band lengths at the first stage, namely, a rapid (over less than in 30 μs) increase in the velocity of the shear band front from zero to a certain maximal value (not smaller than 5 m/s) was not considered because this fast process requires a quite different experimental approach.

For such an approach to detecting the growth of the shear band velocity from zero to a certain maximal value, we propose the acoustic emission method based on the detection of elastic vibrations (acoustic waves) that are generated during the initiation of a shear band [17–20].

The acoustic emission (AE) method proved to be a powerful diagnostic tool for interpreting peculiarities in the evolution of a dislocation structure of a material experiencing deformation (including a metallic glass). The predictability of this tool as regards the emergence of features of a plastic flow and the critical state formation is quite promising both for laboratory tests as in industrial monitoring and diagnostic systems. In this study, we propose a method for reconstructing the shear band length distribution based on the amplitude distribution of acoustic emission signals and demonstrate the existence of scaling effects in the formation and propagation of shear bands in metallic glasses.

2. EXPERIMENTAL TECHNIQUE

As objects of investigation, we chose several glass-forming alloys based on Zr, Ni, and Pd-based alloy systems ($Zr_{60}Cu_{30}Al_{10}$, $Zr_{52.5}Ti_{5}Cu_{17.9}Ni_{14.6}Al_{10}$, $Zr_{64.13}Cu_{5.75}Ni_{10.12}Al_{10}$, $Ni_{40}Cu_{10}Ti_{33}Zr_{17}$, and $Pd_{40}Cu_{30}Ni_{10}P_{20}$ alloys were prepared by pressure casting into a copper crucible as described in [21]. The 3 × 3 ×6 mm samples were tested for compression with simultaneous recording of the acoustic emission signal. A detailed description of this technique can be found in [21]. The $Zr_{64.13}Cu_{5.75}Ni_{10.12}Al_{10}$ samples were tested at rates of 10^{-2}, 10^{-3}, and 10^{-5} s^{-1}, the remaining samples were tested at a rate of 10^{-3} s^{-1}. The acoustic emission signal was recorded continuously with an 18-bit resolution and a discretization frequency of 2 MHz. We used a broadband AE900S-WB sensor. The signal was amplified to 60 dB and was recorded using a PCI-2 system (Physical Acoustic Corp., USA).

From mechanical tests of these samples, we obtained the experimental time dependences of the mechanical stress and the amplitude of acoustic emission signal. By way of example, Fig. 1 shows such dependences, which have been obtained by compressive loading of a bulk $Zr_{60}Cu_{30}Al_{10}$ metallic glass sam-le for a loading rate of 1×10^{-3} s^{-1} [21]. The inset to Fig. 1 shows a fragment of the acoustic emission signal flow, which illustrates the synchronous emergence of acoustic emission pulses and stress jumps due to the initiation and propagation of shear bands that are also shown on the microscopic image obtained using a scanning electron microscope.

Typical amplitude distribution of acoustic emission signals and its approximation by a power-law dis-tribution function, which were obtained during the loading of a $Zr_{64.13}Cu_{5.75}Ni_{10.12}Al_{10}$ metallic glass sample, are shown in Fig. 2. The subsequent analysis revealed that the probability distribution function ofacoustic emission signal amplitudes, which is normalized in amplitude (Fig. 3), is a power-law function, and all experimental data in logarithmic coordinates fit well to the same straight line irrespective of the stoichiometric composition of the metallic glass and the loading rate in mechanical tests.

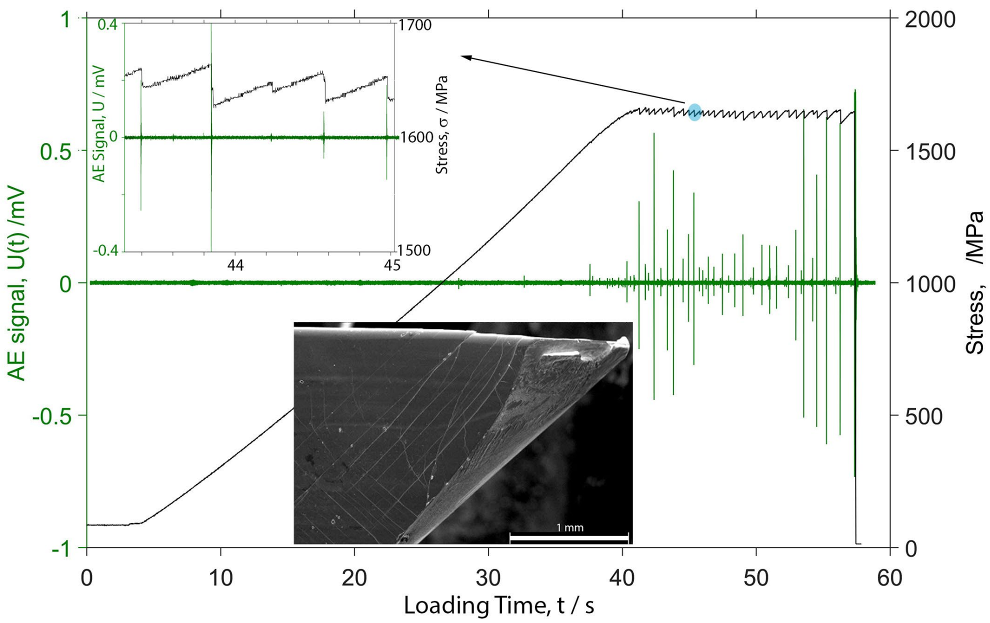

Fig. 1. Experimental mechanical stresses (black color) and amplitudes of acoustic emission signals (green color) as functions of time, which were obtained during compressive loading of a $Zr_{60}Cu_{30}Al_{10}$ bulk metallic glass sample for a loading rate of $1 \times 10^{-3}\ s^{-1}$ [21]. The inset shows a fragment of acoustic emission signal flow, illustrating synchronous emergence of acoustic emission pulses and stress jumps because of the initiation and propagation of macroscopic shear bands, which are also seen in the microscopic image

3. RESULTS AND DISCUSSION

Thus, it follows directly from Fig. 3 that during the initiation of shear bands, the amplitude of acoustic emission signals is a random quantity with the probability distribution density obeying a power law

$$\varphi(U_{AE}) \sim \frac{1}{U_{AE}^{N}}, \text{ где } N = 2.03 \pm 0.12 \qquad (1)$$

The instantaneous acoustic emission power during the initiation of a shear band is estimated as the instantaneous elastic energy relaxation:

$$P_{AE} \sim \frac{d}{dt}\left(\frac{kL^2}{2}\right) \sim kL\dot{L} \sim kLV \qquad (2)$$

where L and V are the current length and velocity ofthe shear band front. The maximal power of the acoustic emission signal at the shear band initiation

:

$$P_{AE}^{\max} \sim k \cdot L \cdot V_{\max} \qquad (3)$$

On the other hand, the acoustic emission signalpower over initiation time τ_i is determined by the mean-square amplitude of the signal in accordancewith the following relation:

$$P_{AE}^{\max} = \frac{1}{\tau_i}\int_0^{\tau_i} U_{AE}^2(t)dt \sim U_{AE}^2 \qquad (4)$$

On account of the uniformly accelerated initiationof the shear band, we have:

$$L = L\left(V_{\max}\right) = \frac{1}{2}V_{\max}\tau_i \qquad (5)$$

Taking this relation into account, we can transform relation (3) to:

$$P_{AE}^{\max} \sim k \cdot L \cdot V_{\max} \sim k \cdot L^2 \qquad (6)$$

With an account for relation (4), we obtain:

$$U_{AE}^2 \sim k \cdot L^2 \text{ или } U_{AE} \sim k \cdot L \qquad (7)$$

Since the probability distribution density is invariant to the normalization in the argument:

$$\int \varphi\left(U_{AE}\right) dU_{AE} = \int \varphi\left(L\right) dL \qquad (8)$$

this immediately implies that the probability distribution densities for two arguments proportional to each other coincide. Formula (1) directly gives:

$$\varphi\left(L\right) \sim \frac{1}{L^n}, \text{ где } n = 2.03 \pm 0.12 \qquad (9)$$

In [14], the following expression was derived for thescaling of the average velocity of a shear band at its deceleration stage:

$$\left\langle V\left(\xi\right)\right\rangle \sim \frac{1}{\xi^\alpha}, \text{ where } \alpha = \frac{n}{n-1} \qquad (10)$$

With an account of (9) we immediately obtain:

$$\left\langle V(\xi)\right\rangle \sim \frac{1}{\xi^{\frac{n}{n-1}}} \sim \frac{1}{\xi^{2}} \tag{11}$$

Thus, we have obtained a power-law distribution ofthe average (or instantaneous within the time measuring error) rate of shear processes in a metallic glass at the stage of conditional deceleration from the maximal velocity to its finalization in the form $\left\langle V(\xi)\right\rangle \sim \frac{1}{\xi^{\alpha}}$, which is confirmed not only by numerous experimental data ($n \sim 2.2...2.8$, $\alpha \sim 1.6...1.8$, [14]), butalso by the results of precision measurements using the AE method, at the stage of the rise of the shear band front (n = α = 2.03 ± 0.12, this study).

Taking $\left\langle V(\tau_i)\right\rangle = V_{\max}$ we immediately obtain:

$$\left\langle V(\xi)\right\rangle = \frac{V_{\max}\tau_i^2}{\xi^2} \tag{12}$$

Integrating this relation with account for condition $L(\xi \to \infty) = L_S$, where L_S is the length of the specimen, we obtain:

$$L(\xi) = L_S - \frac{V_{\max}\tau_i^2}{\xi} \tag{13}$$

Relations (12) and (13) describe the scale invariance of the process of shear band propagation at the conditional deceleration stage in terms of variables $(\xi\,;L_S - L(\xi))$ and $(\xi\,;\left\langle V(\xi)\right\rangle)$, respectively.

As additional argumentation of the approach pro-posted here, which is based on formula (2), we can trace an analogy between seismic shear processes in theearth crust and the evolution of shear bands in metallicglasses. In particular, it is noted in [25] that seismic moment M_0 and the scale of an earthquake of length L (of the shear band length, but only in the case of seismodislocation length) are connected by relation $M_0 \sim L^2$. From the analysis of 1308 seismic events, the following interrelation between the studied seismic energy and the seismic moment was established in [26]:

$$E_S = 2.33\cdot 10^{-6} M_0^{1.04} \tag{14}$$

Or, considering that $M_0 \sim L^2$ we obtain:

$$E_S \sim M_0^{1.04} \sim L^{2.08} \sim L^2 \tag{15}$$

which fully corresponds to formula (2) that has been used for describing the instantaneous elastic energy relaxation in a metallic glass. This confirms once again the possibility of application of the approach proposedhere for describing shear processes in the earth crustalso. It should be noted, however, that in spite of the fact that scale invariance of physical quantities describing shear processes in the earth crust has been confirmed in numerous publications (see, for exam-ple, [27, 28]), it is still the subject of discussions and requires critical analysis in view of the ambiguity of numerical parameters of scaling.

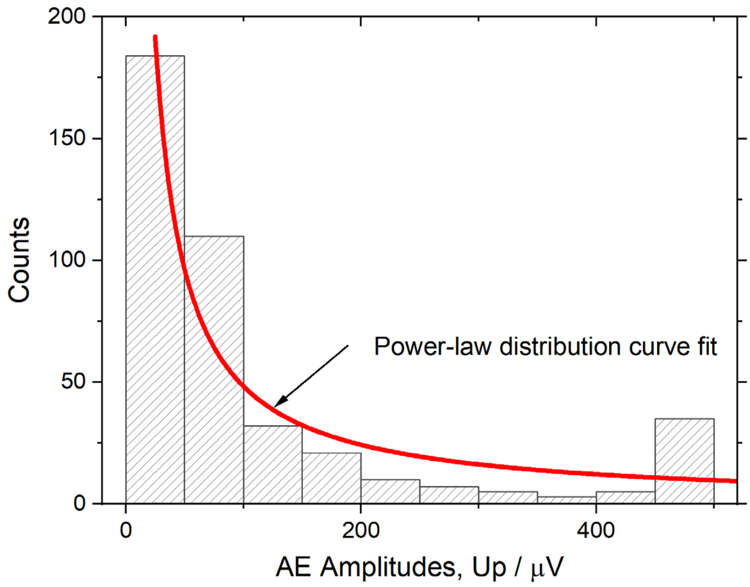

Fig. 2. Typical amplitude distribution of acoustic emission signals and its approximation by a power-law distribution function, which is obtained during loading of a $Zr_{64.13}Cu_{5.75}Ni_{10.12}Al_{10}$ metallic glass sample.

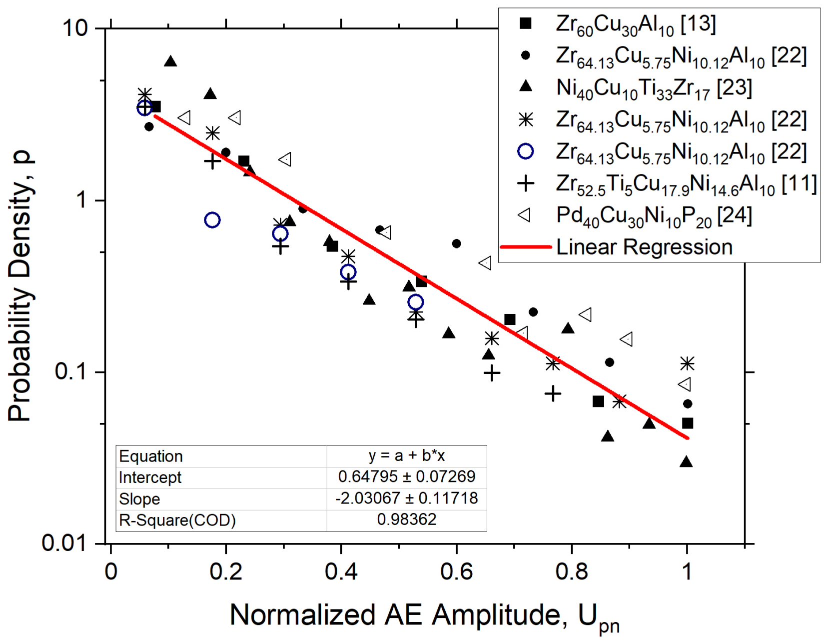

Fig. 3. Amplitude-normalized distribution function of probability density for amplitudes of the acoustic emission signal in studied alloys.

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References

1. James P. Sethna, *Statistical Mechanics: Entropy, Order Parameters and Complexity*, Clarendon Press, Oxford (2017), 371 p.
2. Geoffrey B. West, James H. Brown, Physics Today **57**, 9, 36 (2004).
3. Michael Zaiser, Advances in Physics **55**, 185 (2006).
4. Grigory I. Barenblatt, *Scaling*, Cambridge University Press, Cambridge (2003), 171 p.
5. Keiiti Aki, Paul G. Richards, *Quantitative Seismology: Theory and Methods*, W. H. Freeman and Co., San Francisco (1980), volumes I and II, 932 p.
6. A. Vinogradov, M. Seleznev, I. S. Yasnikov, Scripta Materialia. **130**, 138 (2017).
7. K.A. Dahmen, Y. Ben-Zion, J.T. Uhl, Nature Physics **7**, 554 (2011).
8. J. Antonaglia, W.J. Wright, X. Gu, R.R. Byer, T.C. Hufnagel, M. LeBlanc, J.T. Uhl, K.A. Dahmen, Physical Review Letters **112**, 155501 (2014).
9. G. Wang, K.C. Chan, L. Xia, P. Yu, J. Shen, W.H. Wang, Acta Materialia **57**, 6146 (2009).
10. T.C. Hufnagel, C.A. Schuh, M.L. Falk, Acta Materialia **109**, 375 (2016).
11. D. Klaumünzer, A. Lazarev, R. Maaß, F.H. Dalla Torre, A. Vinogradov, J.F. Löffler, Physical Review Letters **107**, 185502 (2011).
12. A Vinogradov, Scripta Materialia **63**, 89 (2010).
13. M. Seleznev, I.S. Yasnikov, A. Vinogradov, Materials Letters **225**, 105 (2018).
14. I. S. Yasnikov, M. N. Seleznev, A. V. Danyuk, and Yu. Vinogradov, JETP Lett. 110, 436 (2019).
15. S.H. Carpenter, F.P. Higgins, Metallurgical Transactions **8A**, 10, 1629 (1977).
16. T.T. Lamark, F. Chmelik, Y. Estrin, P. Lukac, Journal of Alloys and Compounds **378**, 202 (2004).
17. A. Vinogradov, I.S. Yasnikov, Y. Estrin, Journal of Applied Physics **115**, 233506 (2014).
18. A. Vinogradov, D. Orlov, A. Danyuk, Y. Estrin, Materials Science and Engineering **A 621**, 243 (2015).
19. A. Vinogradov, A. Lazarev, D.V. Louzguine-Luzgin, Y. Yokoyama, S. Li, A.R. Yavari, A. Inoue, Acta Materialia **58**, 6736 (2010).
20. D.V. Louzguine-Luzgin, A. Vinogradov, S. Li, A. Kawashima, G. Xie, A.R. Yavari, Metallurgical and Materials Transactions **A 42**, 1504 (2010).
21. D.V. Louzguine-Luzgin, A. Vinogradov, G. Xie, S. Li, A. Lazarev, S. Hashimoto, A. Inoue, Philosophical Magazine **A 89**, 2887 (2009).
22. A. Vinogradov, A. Danyuk, V.A. Khonik, Journal of Applied Physics **113**, 153503 (2013).
23. C.H. Scholz, Bulletin of the Seismological Society of America **72**, 1 (1982).
24. Г.Г. Кочарян, Г.Н. Иванченко, С.Б. Кишкина, Физика Земли **4**, 141 (2016). (G.G. Kocharyan, G.N. Ivanchenko S.B. Kishkina, Izvestiya, Physics of the Solid Earth **52**, 606 (2016).)
25. J.G. Anderson, S.G. Wesnousky, M.W. Stirling, Bulletin of the Seismological Society of America **86**, 683 (1996).
26. Jeen-Hwa Wang, Terrestrial Atmospheric and Oceanic Sciences **29**, 589 (2018).